Chemical Ionization Mass Spectrometry with Lithium Ion Attachment to the Molecule

Toshihiro Fujii,* Miyoshi Ogura, and Hitoshi Jimba

National Institute for Environmental Studies, Tsukuba, Ibaraki 305, Japan

This report describes a new development for chemical ionization mass spectrometry (CIMS) that provides mass spectra consisting of quasi-molecular ions, $(M + Li)^+$, by lithium ion attachment to the sample molecules (M) under high pressure. Lithium ions are generated by heating lithium oxide in an aluminosilicate matrix in a flowing nitrogen gas stream. Alkali-metal ions attach to the sample in the carrier gas in termolecular reactions to produce $(M + Li)^+$ ions. The lithium ion CI source is attached to the three-stage differentially pumped mass spectrometer with the first cone aperture (0.5 mm i.d.) through which the product ions enter the mass analysis region. The identification and detection of acetone are described as an example of the utility of this new CI ion source. Analysis of a formulated gas sample with direct introduction to the CI source is also demonstrated.

INTRODUCTION

Chemical ionization mass spectrometry (CIMS) has proven to be a sensitive method that is complementary to electron impact ionization mass spectrometry for the determination of components of biological, air, and environmental samples. It has been successfully interfaced to the gas chromatographic system. Recently, a book has been published (1) on the principles, instrumental techniques, unique characteristics, and applications of CIMS.

Recently many articles have appeared in the literature concerning the gas-phase chemistry of alkali-metal ions with organic molecules (2–5), which has been often observed in low-energy ionization processes, i.e. chemical ionization, field ionization, field desorption, electrohydrodynamic ionization, fission fragment induced desorption, laser induced desorption, secondary ion mass spectrometry, and thermal ionization. Alkali-metal ions such as Na^+ form adduct ions (also referred to as cationized molecules) of the type $(M + Na)^+$. Rollgen's group (6) explored three different methods for achieving cationization using the field desorption technique.

In general, cationized molecules are more stable than radical molecular ions or protonated molecules. The fragmentation of the polar molecules resulting from cationization by alkali-metal ions (alkali-metal ion attachment) has a higher activation energy than splitting off functional groups after a protonation. Cationization is, therefore, potentially useful for the determination of molecular weights. The important question is the feasibility of using the advantages of cationization for CIMS as a new ionization method.

Hodges and Beauchamp (7) described a technique for obtaining mass spectra consisting solely of quasi-molecular ions formed by addition of Li^+ ions to the sample molecules. This demonstrated that alkali-metal ion CI mass spectrometry is a useful addition to the field of analytical mass spectrometry. Potassium ion CI was also used (8) to ionize certain compounds selectively in a mass spectrometer source. However, neither study made an attempt to extend and determine the ultimate sensitivity of alkali-metal ion CI mass spectrometry.

The purpose of this study is to construct an optimized Li^+ ion source (LIS), to report response and performance char-

acteristics for acetone, and to demonstrate the LIS as a new sensitive ionization source for CIMS. This system employs a thermionic alkali-metal ion emitter in a flow of nitrogen buffer gas in high-pressure mass spectrometry with ion counting. Experimental conditions and some applications are discussed.

EXPERIMENTAL SECTION

All experiments were performed with a Shimadzu atmospheric pressure ionization mass spectrometer with a lithium ion source.

Lithium Ion Source. The lithium ion source (LIS) constructed for this work was a modification of the previously reported filament sources for positive ions (9). Shown in Figure 1 is a schematic diagram of the LIS and ion optics. The LIS consists of a lithium ion emitter, reaction chamber, and repeller.

Lithium ions are emitted from the lithium ion emitter, which is a small mineral bead (about 2 mm in diameter) fused to a 0.1 mm diameter Pt filament wire. The bead is prepared with a thoroughly ground mixture of $Li_2O:Al_2O_3:Si_2O$ in a 1:1:1 molar ratio for Li^+ alkali-metal ions. Primary ions are produced in the carrier gas by heating the bead. The filament power was kept less than 1 W to reduce heating effects.

Under these operating conditions, the lifetime of a filament is over 100 h. For the first few hours of operation, emission of the contaminants of other alkali-metal ions may be significant. These subsequently decrease to less than 0.1% of the total emission.

The bead is placed 10 mm from the cone. The reaction chamber is a cylindrical tube (i.d. 20 mm) with the lithium ion emitter centered within the chamber. The chamber can be heated to 250 °C and evacuated through the cone aperture with a 500-L/min rotary pump and maintained at CI pressure conditions (1–760 Torr) by changing the pumping speed or the carrier gas flow rate. The chamber pressure was measured with a pirani gauge (PG-3A, Wakaida, Tokyo) that had been calibrated for N_2. The repeller electrode is made of a 15 mm diameter stainless steel disk, which is 10 mm behind the bead. The repeller voltage was maintained at the same potential as the emitter.

Sampling Interface. The sample gas from the aperture of the cone impinges on the skimmer, in the tip of which a 1 mm diameter orifice was drilled. No potentials were applied to the skimmer.

Vacuum System. The system is evacuated differentially by three pumps. The reaction chamber into which the sample gas was introduced through the carrier gas flow line is maintained at 1–760 Torr by a rotary pump. The lens region ahead of the quadrupole mass spectrometer (QMS) is held at less than 2×10^{-4} Torr by a 1500-L/s diffusion pump. The QMS region is evacuated by a 500-L/s diffusion pump around 5×10^{-7} Torr.

Electrostatic Lens. As shown in Figure 1, the lens system consisted of an extractor, deflectors, and four sets of coaxial, sequential cylinders, each biased at a particular direct current (dc) voltage. Maximum ion signals were obtained at the voltages specified in the caption of Figure 1.

Mass Analyzer. The QMS was used without the electron impact ionizer. The rods were biased below ground by connecting separate dc supplies into the dc rod driven circuit (10).

Ion Detection System. The channeltron electron multiplier detector was operated both in the pulse-counting mode and in the analog mode. The pulses were channeled from the multiplier output to a preamplifier–discriminator–counter system, which is operated in the multichannel scaling mode. For mass spectrometric measurement, two modes of ion detection were usually employed.
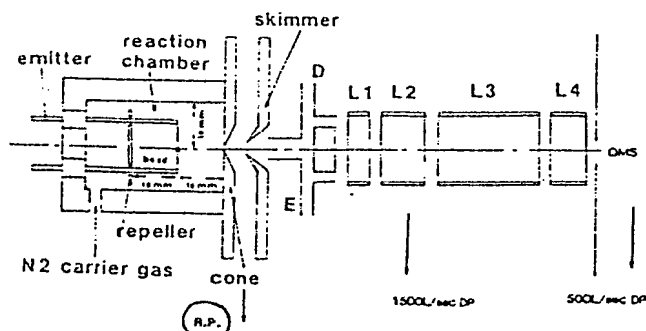
$5 \, m\ell/m$

Figure 1. Schematic diagram of the lithium ion source and ion optics: E, extractor (–70 V); D, deflectors (*x, y* direction); L1, lens 1 (–20 V); L2, lens 2 (–10 V); L3, lens 3 (–70 V); L4, lens 4 (–10 V).

Operational Procedure. The characterization study of the present source was carried out with reference compounds through a standard gas generator. By use of a permeation tube (*11*), acetone was diluted in pure nitrogen gas to produce the standard mixtures. The acetone was used to characterize the LIS response and performance.

The acetone permeation tubes were prepared from different Teflon tubing. Each tube was filled with liquid acetone, and the end was plugged tightly. These tubes had permeation rates of 7×10^{-11}, 1×10^{-10}, 2.6×10^{-10}, and 8.2×10^{-10} g/s at room temperature. These permeation tubes required several days before constant permeation rates were achieved.

RESULTS AND DISCUSSION

Lithium Ion Intensity. We tested the lithium ion emitter at different temperatures. A simple diode arrangement (*12*) was used to measure the lithium ion emission current; it consists of an emitter and an ion collector that is 300 V positive with respect to the emitter. The maximum emission current of Li^+ ions was measured around 6×10^{-7} A. The life span of this emitter with the heating current at 2.0 A is about 100 h.

The Li^+ ion density in an ion source is estimated by a simplified treatment (*13*). At steady state, the total loss rate is exactly equal to the production rate. The ion production rate is assumed to be 3.8×10^{12} ions/s, which corresponds to the maximum lithium emission current. Ion loss is mainly due to flow and diffusion to walls. The flow loss rate is estimated as follows: When the nitrogen gas flow of 5 mL/min passes through the ion source at 1 Torr, the gas flow is

$$5/60 \times 760/1 = 63 \text{ cm}^3/\text{s} \qquad (1)$$

If the lithium ion density is n ions/cm^3, then the flow loss rate is $63n$ ions/s. The wall loss rate by the process of diffusion is given as

$$Wn = (V/t_0)n = (2.2 \times 10^3)n \text{ ions/s} \qquad (2)$$

where V, the ion chamber volume, has been taken as 6.28 cm^3. t_0 is the characteristic time for an ion to diffuse through the gas to the container wall, which is estimated by

$$r_0 = 2(Dt_0)^{1/2} \qquad (3)$$

when r_0 is the radius of the container, and D is the diffusion coefficient that is obtained from the reduced ion mobility, using the Einstein relation (*14*). The reduced ion mobility is directly accessible from ion drift theory (*14*).

Thus, setting the production rate equal to the total loss rate gives the lithium ion density at 1 Torr:

$$63 + (2.2 \times 10^3))n = 3.8 \times 10^{12},$$

$$n = 1.7 \times 10^9 \text{ ions/cm}^3 \qquad (4)$$

The lithium ion current into the lens region vacuum through the skimmer, I_0, is estimated as follows. It is observed that the 1500-L/s second-stage pump is loaded to give a lens region of 2.7×10^{-6} Torr with a skimmer orifice 1 mm in diameter.
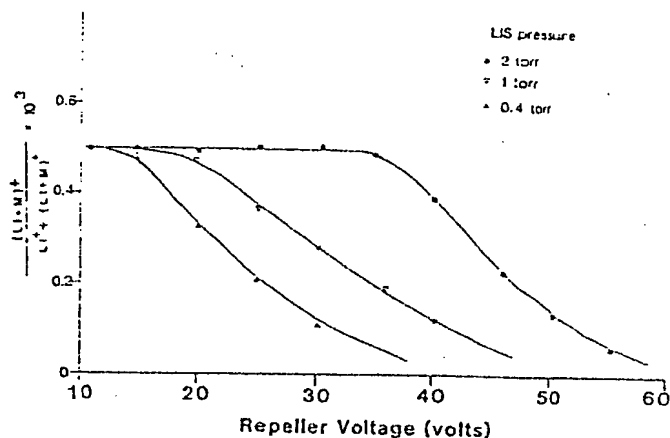

Figure 2. Plot of $I(Li + M)^+/[I(Li)^+ + I(Li + M)^+]$ vs repeller voltage at various pressures (Torr). M: acetone.

Thus the amount of the N_2 gas flow into the lens region vacuum is calculated as

$$1500 \text{ (L/s)} \times (2.7 \times 10^{-6}) \text{ (Torr)} =$$
$$4.1 \times 10^{-3} \text{ molecules cm}^3/\text{s} \qquad (5)$$

and then

$$I_0 = (4.1 \times 10^{-3})(1.7 \times 10^9)(760/1) = 5.3 \times 10^9 \text{ ions/s} \qquad (6)$$
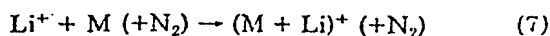
Reactions in Source. Ionization in this source is initiated by formation of alkali-metal ions on the emitter. A successful method for obtaining lithium ion cationization mass spectra must provide a means for binding lithium ion to the sample molecules. Lithium ions can be injected into an inert gas, such as nitrogen, that contains a trace amount of sample, and (M + Li)$^+$ complexes are formed by termolecular association reactions. The ionic products observed are a reflection of association reaction rates.

The formation of an addition ion is commonly assumed to be a three-body process, in which a neutral molecule collides with an ion–molecule complex and removes an amount of energy, stabilizing the (M + Li)$^+$ complex. Based on this model, the cationization process would be suitable in a high-pressure environment, since the added gas molecules serve as the third bodies in the analyte addition reaction with alkali-metal ions.

The abundance of attachment products was greatly influenced by the voltage applied to the repeller, which provides the reactant ion with kinetic energy. The relationship of $I(M + Li)^+/[I(Li)^+ + I(M + Li)^+]$ to the repeller voltage was examined at various source pressures, using acetone as the analyte. As can be seen from Figure 2, the fraction present as Li^+ adduct ion decreases with increasing repeller voltage. At the higher ion source pressure, more adduct ions were produced at the higher repeller voltage. Low repeller voltage (E) and high ion source pressure (P) favor adduct formation; as E/P is raised, the probability of this process decreases.

This ion energy dependence is consistent with the reported mechanism of the ion attachment reaction: The initial combination step of an ion–molecule association reaction is brought about by ion/dipole attraction between the reactants without any activation energy.

Sensitivity Considerations. For lithium ion association with most organic molecules, bimolecular kinetics was observed with an ion chamber pressure of greater than 1 Torr (*15*). Therefore, the sensitivity can be evaluated by using the following reaction equation:

$$Li^+ + M \ (+N_2) \rightarrow (M + Li)^+ \ (+N_2) \qquad (7)$$
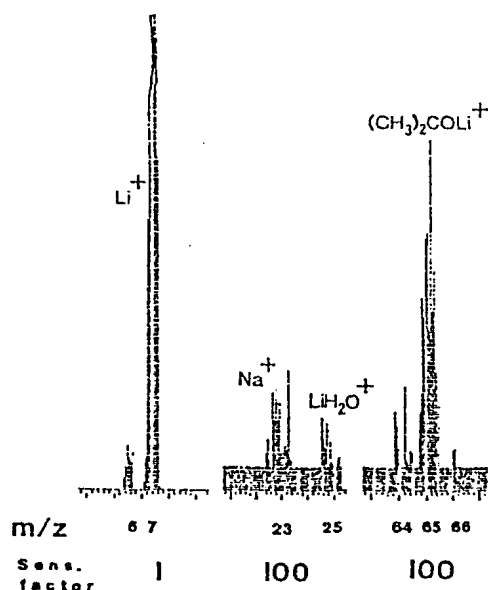
The decrease in the lithium ion Li^+ in the reaction chamber

Figure 3. Spectrum obtained from acetone samples in nitrogen gases showing $(CH_3)_2COLi^+$ (m/z 65). Samples were introduced through the standard gas sampler at the rate of 2.6×10^{-10} g/s.

as a consequence of the addition of organic reactant M is given by

$$d[Li^+]/dt = -k[Li^+][M] \qquad (8)$$

where k is the binary rate constant for reaction 7. When $[Li^+]_0$ is the concentration of Li^+ prior to the introduction of the sample gas M, l (1 cm) is the length of the reaction zone, r_0 is the radius of the container tube, v_0 is the average flow velocity, and Q (particles/s) is the rate of introduction of M, eq 8 is integrated (16)

$$\ln [Li^+]/[Li^+]_0 = -Qkl/3.14 \, r_0^2 v_0^2 \qquad (9)$$

$$[(M + Li)^+] = [Li^+]_0 - [Li^+] \qquad (10)$$

The average flow velocity is defined as

$$v_0 = [F \text{ (atom cm}^3\text{/s)}/3.14 r_0^2 \text{ (cm}^2)] \times$$
$$[760 \text{ (Torr/atom)}/P \text{ (Torr)}] \qquad (11)$$

where P is the pressure in the ion chamber. When P is 1 Torr, $v_0 = 20.2$ cm/s. Assuming that k, the effective bimolecular rate constant (15) of the termolecular reaction in the 1-Torr buffer gas environment, is 1×10^{-10} cm^3/(molecule s), and the fraction of ions transmitted from source to detector is 1×10^{-3}, based on a factor of 0.1 for the ion lens and 0.01 for the mass analyzer, the sensitivity expressed in A/(g/s) can be calculated as approximately $\underline{6.6 \times 10^{-4} \text{ A/(g/s)}}$ for the case of the acetone introduction rate of 10^{-10} g/s.

Figure 3 shows three mass spectra around m/e 7, 23, and 65, respectively, in which the primary ions, Li^+ and Na^+, and the Li^+ attachment ion, $(CH_3)_2COLi^+$, are monitored. The acetone sample is introduced at a rate of 2.6×10^{-10} g/s from the permeation tube at 25 °C. The measurement of the adduct ion yielded a value of 2.9×10^{-10} A, which is the output of the ion multiplier with the gain at 2×10^3; this current corresponds to 1.5×10^{-13} A (9.4×10^5 ions/s). Thus, the sensitivity is $\underline{5.8 \times 10^{-4} \text{ A/(g/s)}}$. In comparison with the calculated sensitivity, slightly worse sensitivity has been actually demonstrated, confirming the conservative, but essentially correct, nature of the previous estimate of the effective bimolecular rate constant.

Taking the actual noise level of the system as the ultimate limitation on minimum detectable sample size, we can estimate the minimum detectable amount (mda). The background rate of our ion counting system is typically 10 counts/s

with all components operating. As a practical and conservative lower limit of quantitative detectability, a signal to background ratio of 10 may be required. Then, for a continuous sample, we require 100 counts/s. Taking the sensitivity for acetone, which was determined to be 5.8×10^{-4} A/(g/s) experimentally, we estimated that the mda is around $\underline{2.8 \times 10^{-14}}$ g/s. By the same token, in the analog detection mode, the mda is calculated to be $\underline{3.4 \times 10^{-12}}$ g/s on the assumption that the capability of the ion detection system in the analog mode at the signal to noise ratio of 3 is around 2×10^{-15} A.

Linear Response Range. Signal response was linear over the chosen range of 7×10^{-11} to 8.2×10^{-10} g/s for the acetone. A plot of four introduction rates of acetone against their corresponding peak heights produced an essentially straight line up to 8.2×10^{-10} g/s, where more than 5% of the total Li^+ reactant ions is used for the attachment.

In a manner identical with that of the electron capture detector the response follows Beer's law because the sample, as it is cationized, depletes the alkali-metal ion density. Therefore, for a linear response, the sample size must ensure a large excess of reactant ions in the cationizing chamber.

Background Mass Spectra. The accumulated background spectrum was obtained in the $100\times$ recurrent multiscaling mode. The scan time was 5 s, and the scanning mass range was 5–150 amu. Consistent background mass spectra were obtained after increasing the reaction chamber and inlet temperature to 250 °C overnight with a flow of the carrier gas. The background mass spectrum generally shows an abundant H_2OLi^+ as well as other alkali-metal ions with a low intensity peak at m/z 30, 31, 35, 42, 55, 56, 65, and 114. The emission of alkali-metal ion contaminants hinges on the heating condition: The distribution primarily depends on the aging temperature and time. H_2OLi^+ is probably derived from the ever-present water in the nitrogen carrier gas. From close inspection of isotope ratios, m/z 30 and 31 may be assigned to Li_2OH^+. The m/z 65 peak is due to Li^+ attached to acetone, which is attributable to the presence of acetone used previously as the test sample. The peaks m/z 35, 42, 55, 56, and 114 are persistent. They have yet to be assigned. Presumably, the limit of detectability is determined mainly by the impurity content of the emitter bead.

Analysis of Gas Sample. The Li^+ CI mass spectrum was taken in the single-scan mode for a formulated mixture of six compounds in N_2 gas. The sample gas was introduced directly to the source at a flow rate of 5 mL/min. The sample components were CH_3CN, CH_3CHO, $(CH_3)_2CO$, C_3H_7OH, $(C_2H_5)_2NH$, and C_6H_6. Only the quasi-molecular species, Li^+ complexes, are present, demonstrating that Li^+ ion chemical ionization mass spectrometry will find numerous applications in the analysis of mixtures. The alkali-metal ion CI appears to have advantages over conventional CI with CH_4, since more than one reactive species is generated in the CI (CH_4) source, and it does not always provide the single ion species.

CONCLUSION

This study has demonstrated that the Li^+ ion source is a novel, sensitive, and unique mass spectrometric CI ion source. The particular advantage of this method lies in the generation of ions that do not fragment. This ionization method is of interest for the determination of molecular weight and analysis of mixtures where no fragmentation is desired.

Many other alkali-metal species have been used as reactant ions. The affinity of the species, which decreases as the metal is varied from Li^+ to Rb^+, is the variable that can be adjusted to provide a selective ionization method.

The ionization efficiency in the $(M + Li)^+$ ion formation is strongly dependent on the Li^+ affinity of the molecule, which ranges up to about 50 kcal/mol. Unfortunately, there is not yet a body of literature about many molecules. However, the

wealth of information about the polarity and the polarizability is useful in predicting which molecule can be detected at a low-level concentration, because it is known that the affinity increases with the polarity and to a lesser degree with the polarizability of the molecules (17).

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